REMOTE TEMPERATURE SENSING WITH LOW-THRESHOLD-POWER USING ERBIUM-DOPED FIBER LASER

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I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged

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I personally dedicate this to:

My beloved parents,

Families,

Supervisors,

Good friends,

And everyone who has been supporting me all this time

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ABSTRACT

Remote temperature sensing is of significant interest nowadays as it can continuously monitor structures located at tens or hundreds of kilometers away from a central location. With remote sensing, any damage of structures can be detected immediately, thus appropriate action can be taken quickly. Optical fiber laser temperature sensor is one of technologies that can be used for the implementation of remote temperature sensing. Few developments have been reported regarding the use of fiber laser for remote temperature sensing. However, in general they use Raman amplifiers which have relatively high threshold power of higher than 1 W to trigger the laser and this consequently increases the total cost for the implementation. Motivated to achieve a lower threshold power, this thesis presents a remote temperature sensor that utilizes erbium-doped fiber laser (EDFL). The configuration of the laser cavity is linear, comprising a fiber mirror reflector at one end, and the other end is formed by a fiber Bragg grating (FBG) with central wavelength of 1560 nm as the sensor head. A 30 km single mode fiber is placed before the FBG to serve as a transmission channel for remote sensing and erbium-doped fiber amplifier (EDFA) as the gain medium. The EDFA is used because it can operate using low pump power owing to the high gain efficiency of the doped-fibers. Based on this proposed design, experimental results indicate that it has a low threshold pump power of only 12 mW. In comparison to the previous study, the obtained threshold power presents an improvement of 98.8%. In addition, the laser has good stability with power fluctuations of less than 1.2 dB over a 30 minute duration, OSNR of 49 dB and power efficiency, up to 0.07%. With this fiber laser, a temperature sensor with a sensitivity of 10.6 pm/°C is realized for a temperature range from 30 °C to 90 °C which has potential to be applied in the oil and gas field. This sensitivity value is comparable with those obtained with Raman-based fiber lasers, albeit with the requirement of lower threshold pump power. The 98.8% reduction of the threshold power requirement presents opportunity for more cost effective operation in the implementation of remote temperature sensing.

ABSTRAK

Penderiaan suhu jarak jauh penting ketika ini kerana dapat melakukan pemantauan berterusan terhadap struktur yang terletak puluhan atau ratusan kilometer dari lokasi pusat. Dengan penderiaan jauh, kerosakan struktur dapat dikesan dengan segera agar tindakan yang tepat dapat diambil dengan cepat. Penderia suhu laser gentian optik adalah salah satu teknologi yang dapat digunakan untuk pelaksanaan penderiaan suhu jarak jauh. Beberapa perkembangan telah dilaporkan mengenai penggunaan laser gentian untuk penderiaan suhu jarak jauh. Walaubagaimanapun, secara amnya mereka menggunakan penguat Raman yang mempunyai kuasa ambang yang agak tinggi melebihi dari 1 W untuk menghasilkan laser dan seterusnya meningkatkan kos pelaksanaannya. Bermotivasi untuk mencapai kuasa ambang yang lebih rendah, tesis ini membentangkan penderiaan suhu jarak jauh menggunakan laser gentian berdopkan erbium (EDFL). Konfigurasi laser adalah selari, terdiri dari pemantul cermin gentian di hujungnya, dan di hujung yang lain ialah gentian bragg gerigi (FBG) dengan gelombang pusat 1560 nm. Gentian mod tunggal (SMF) sepanjang 30 km diletakkan sebelum FBG berfungsi sebagai saluran penghantaran untuk penderian jauh, manakala penguat gentian berdopkan erbium (EDFA) digunakan sebagai medium gandaan. EDFA digunakan kerana beroperasi dengan kuasa pam yang rendah kesan dari kecekapan gandaan yang tinggi dari gentian berdop. Berdasarkan reka bentuk ini, hasil eksperimen menunjukkan kuasa pam ambang yang rendah dengan hanya 12 mW. Jika dibandingkan dengan kajian sebelumnya, kuasa ambang yang diperoleh menunjukkan peningkatan sebanyak 98.8%. Selain itu, laser mempunyai kestabilan yang baik dengan turun naik kuasa kurang dari 1.2 dB dalam jangka masa 30 minit, OSNR 49 dB dan kuasa kecekapan sehingga 0.07%. Dengan laser gentian ini, penderia suhu dengan kepekaan 10.6 pm/°C direalisasikan untuk julat suhu dari 30 °C hingga 90 °C yang berpotensi untuk digunakan di bidang minyak dan gas. Nilai kepekaan ini setanding dengan keputusan yang diperoleh berasaskan Raman, walaupun dengan kuasa pam ambang yang lebih rendah. Pengurangan 98.8% dari keperluan kuasa

ambang memberi peluang untuk operasi yang lebih efektif dari segi kos dalam pelaksanaan penderiaan suhu jarak jauh.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	-	Ampere
B	-	Birefringent
cm	-	centimeter
dB	-	decibel
GHz	-	Giga Hertz
km	-	kilometer
L	-	Length
m	-	meter
m	-	diffraction
mW	-	mili Watt
δ	-	Phase Difference
n	-	Refractive index
n_{eff}	-	Effective refractive index
n_f	-	Effective indices in fast mode
n_s	-	Effective indices in slow mode
nm	-	nanometer
pm	-	picometer
W	-	Watt
℃	-	Degree celcius
α	-	Thermal Expansion Coefficient
p	-	Optical coefficient of torsion
μ	-	Micrometer
∆T	-	Temperature change
$\Delta\epsilon$	-	Change of strain
Λ	-	Length of the period grating
λ	-	Wavelength

λ_B	-	Bragg Wavelength
λ_{res}	-	Resonant Wavelength
ξ	-	Thermo Optic Coefficient
θ_1	-	Angle of incident light
θ_2	-	Angle of diffraction wave
π	-	Pi
ASE	-	Amplified spontaneous emission
AWG	-	Arrayed Waveguide Grating
CW	-	Clockwise
CCW	-	Counter clockwise
CFBG	-	Chirped Fiber Bragg Grating
DCF	-	Dispersion Compensating Fiber
DFA	-	Doped Fiber Amplifier
DFB	-	Distributed feedback
EDF	-	Erbium Doped Fiber
EDFA	-	Erbium-doped Fiber Amplifier
EDFL	-	Erbium-doped Fiber Laser
ESA	-	Electrical Spectrum Analyzer
ESD	-	Electrostatic Discharge
FBG	-	Fiber Bragg Grating
FFPF	-	Fiber Fabry-Perot Filter
FMF	-	Few-mode fiber
FP	-	Fabry Perot
FPI	-	Fabry-Perot Interferometer
FRA	-	Fiber Raman Amplifier
FWM	-	Four-wave mixing
LD	-	Laser Diode
LPG	-	Long Period Grating
MI	-	Michelson Interferometer
MLM	-	Multi longitudinal mode
MZI	-	Mach-Zender Interferometer
OBPF	-	Optical Band Pass Filter
OFG	-	Optical Fiber Grating

OSA	-	Optical Spectrum Analyzer
OSNR	-	Optical-Signal-noise Ratio
OPM	-	Optical Power Meter
OTBF	-	Optical Tunable Band pass Filter
PC	-	Polarization controller
PCF	-	Photonic Crystal Fiber
PI	-	Poly-Imide
RS	-	Rayleigh Scattering
RDFB	-	Random distributed feedback
RDFL	-	Random distributed fiber laser
SBS	-	Stimulated Brillouin Scattering
SI	-	Sagnac Interferometer
SLM	-	Single longitudinal mode
SMF	-	Single mode fiber
SMS	-	Single mode-multi mode-single mode
SOA	-	Semiconductor Optical Amplifier
TDFA	-	Thulium-doped Fiber Amplifier
TFBG	-	Tilted Fiber Bragg Grating
WDM	-	Wavelength division multiplexing
XPM	-	Cross-phase modulation
YDFA	-	Yterrbium-Doped Fiber Amplifier

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The invention of optical fiber laser has caused this field to experience incredible growth and advancement. This is due to the advantages of optical fiber laser which has driven researchers to be innovative and consequently to have a place in a wide field of applications. These applications include the area of imaging, optical communication, spectroscopy and optical sensing [1]. Hence, in focusing on the development in optical sensing, optical fiber laser can be used to detect various environmental measurements such as temperature, strain, vibration and pressure [2]–[4].

Specifically, temperature sensing technologies based on optical fiber has several advantages to offer over the traditional electrical temperature sensor that make them appealing in a lot of industrial sensing applications. The optical fiber sensor are naturally lightweight and small in size that makes them easy to integrate, do not conduct an electric current and immune to electromagnetic and radio frequency interferences. Besides, they are also robust and resistant against harsh environment, capable to perform remote and distributed sensing and last but not least they are able to withstand high temperature [5]–[7].

The application of optical fiber in sensing technologies is incredibly significant as it involves a diverse range of applications. For instance, it is often exploited in harsh environment area since conventional electrical sensor like thermocouple has turned out to be ineffective in these areas due to their characteristic that is unfit for the harsh environment condition [5]. In such an environment, potential hazardous gases and voltages might exist, therefore, since optical fiber sensors are robust and non-corrosive, they are a suitable option. Also, the capability of optical sensor to withstand high temperature helps them to work well under those circumstances. Whereas, their immunity towards electromagnetic interference will be benefitted to reduce the difficulty to obtain signals [8].

Additionally, their application is not only limited to the harsh environments, but also in biomedical applications. A study has categorized them into physical, chemical and bio-sensor measurands of healthcare. In [9] parameters such as temperature, it is measured through physical measurands. Here, they measure the temperature distribution in liver tissue by measuring the changes in Rayleigh backscattering signal in optical fiber [9]. In a different development, optical fiber was used in vivo brain temperature measurements. The sensor is tested to measure the brain temperature of rats for the in vivo method where a rare earth glass is deposited on the tip of fiber [10]. All these applications are strong evidence that shows the importance of optical fiber sensors in technology development. There are other applications of optical fiber sensor for temperature parameters in biomedical applications being discussed with detail in [2].

Since optical fiber temperature sensors are widely used in applications, there are many configurations, methods and techniques that have been demonstrated. One of the methods that needs to be highlighted here is based on optical grating. This method requires a type of optic fiber with a periodic grating of different refractive index that is sensitive towards the external environment such as temperature and strain. Once changes occurred in the environment, it causes the refractive index of the optical fiber to change and results in the filtered wavelength to shift. Optical grating-based method involves a certain type of fiber such as fiber Bragg grating (FBG), Long-period grating (LPG), chirped period grating and tilted period grating. Other methods that have been demonstrated include interferometry and intensity based technique.

In summary, the development of the optical fiber temperature sensor is extremely beneficial to a broad area of applications. This explains, the need for extensive study in this area so that the new technology could cater for the demands in the related industry. Therefore this research project aims to develop an optical fiber laser for a remote temperature sensor with a low threshold pump power. By having a type of configuration that is able to attain a low threshold power, it will be advantageous in reducing cost as only a small amount of pump power is required to obtain a maximum laser power.

1.2 Problem Statement

In the development of a fiber laser for remote temperature sensing, an amplification gain is required to assist the fiber laser to achieve sufficient gain. Previously, in [11]–[14] the early development of these fiber laser temperature sensors employ Raman amplification as the gain medium. Despite the successful detection of temperature sensing based on Raman gain, they have a disadvantage where this design requires a high pump power for operation. This is due to the characteristic of the Raman gain. Inspired to obtain lower threshold power, a Raman-EDFA (Erbium-doped Fiber Amplifier) hybrid gain is being introduced in the cavity design to get lower threshold power than the previous Raman gain amplification [15]. Then, in another development, erbium-doped fiber (EDF) was made solely used as the gain medium. This study successfully obtained a low threshold power; however, it suffers from laser instability due to the use of randomness of random grating in the laser cavity [16].

Motivated to achieve a lower threshold power with high laser stability in remote temperature sensing has led to the development of this research work. A lower threshold power in a fiber laser temperature sensor performance offer an advantage in operating cost. It is better to achieve a low threshold power because it defines a low amount of pump power needed to generate a laser. Hence, with a low pump power required to generate a laser, the operating cost to implement a remote sensing fiber laser will also be reduced. This proposed laser achieves stability at low threshold power due to the avoidance of laser randomness in the laser cavity.

1.3 Research Objectives

This work is aimed to develop a remote temperature sensing with a low-threshold-power erbium-doped fiber laser. Particularly, there are three objectives that need to be achieved to support the aim which are as follows;

i. To develop a fiber laser cavity for a remote temperature sensing based on Fiber Bragg Grating (FBG).
ii. To investigate the laser cavity performances in terms of laser threshold power, spectrum evolution, stability and peak power fluctuation, optical signal-noise ratio (OSNR) and the 3 dB bandwidth of laser.
iii. To analyse the temperature sensing performances in terms of wavelength shifting and sensitivity.

1.4 Research Scope

To concentrate on the goals and contribution of this research project, there are a few scopes and limitation to restrict the investigation. Figure 1.1 is included to aid the explanation of research scope as follows;

i. A fiber laser temperature sensor requires a sensing head to detect any environmental changes. There are several techniques and types of sensing head that can be utilized such as using an optical fiber grating (OFG) or interferometer. A type of OFG known as fiber bragg grating (FBG) is used as the sensing head in this experimental setup.
ii. Optical fiber temperature sensors can be developed based on a broadband light source signal or a narrow beam fiber laser. In this research experiment, the temperature sensor is developed based on a fiber laser generated from a fiber laser cavity.
iii. A fiber laser cavity can be designed as a ring cavity or as a linear cavity. In this research experiment, the experimental setup is designed for a linear cavity configuration.
iv. In accordance with a fiber laser cavity development, a medium gain in an optical amplifier is required for signal amplification. There are many

alternative types of optical amplifier depending on their characteristics and behaviours. This includes Raman amplifier, Parametric Amplifier, Semiconductor optical amplifier and erbium-doped fiber (EDFA). However, in this research project, the focus is on the EDFA as the optical amplifier.

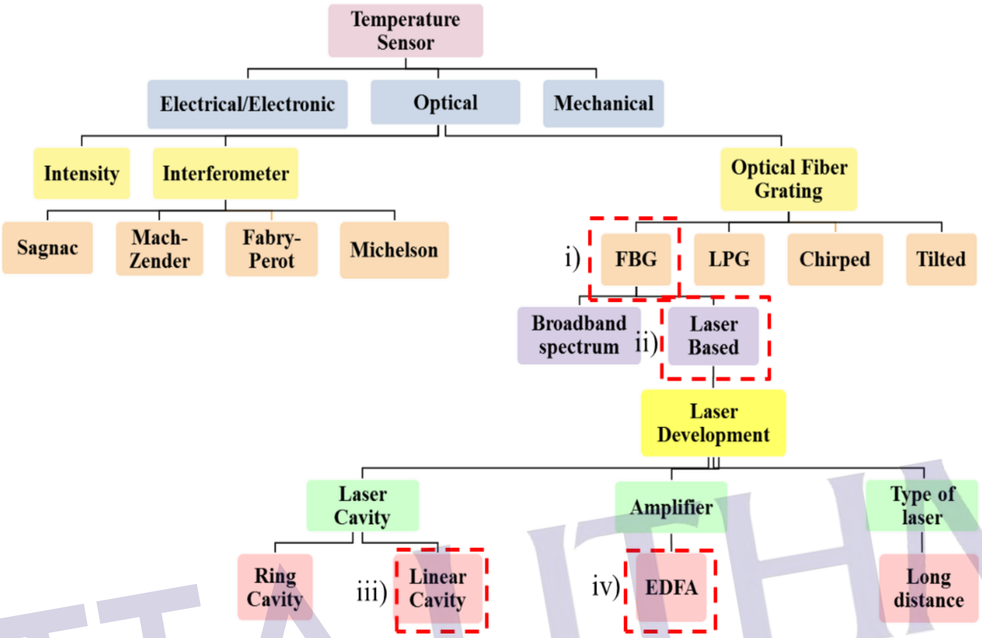

Figure 1.1: Research Scope

1.5 Research Contribution

i) The formation of a new cavity design for a fiber laser remote temperature sensing based on FBG. The new design involves a linear cavity design with both ends formed by the fiber mirror reflector and the FBG. It also utilizes an EDFA as the optical amplifier.

ii) The improvement in a fiber laser temperature sensing performances in terms of threshold power. Previous studies offer a higher threshold power due to the Raman gain utilization.

iii) The simplicity of the cavity design which leads to fewer components needed and easy to implement but can still achieve high stability.

1.6 Thesis Outline

This report consists of five chapters that are organized as follows:

i. Chapter 1: Introducing the research background of this research project, the problems that motivate this research development, the objectives as well as the scope and the contribution.
ii. Chapter 2: Providing the introduction to temperature sensor, as well as the classification and fundamentals of optical temperature sensors based on its method and type optical amplifier. Also discussed is the previous research related to the research project.
iii. Chapter 3: Discussing the methodology of the experiment and the mechanism of how the experimental setup works as the temperature sensor.
iv. Chapter 4: Presenting the result and analysis of the data obtained from the experiment.
v. Chapter 5: Concluding the overall research study and suggestions for future works.

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